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Diode-Laser-Pumped, Gas-Cell Atomic Clocks

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Recent theoretical calculations suggest that the short-term stability of rubidium, atomic, gas-cell frequency standards could be improved by several orders of magnitude if diode lasers were used for optical pumping. Moreover, the theoretical results predict that rubidium, as opposed to cesium, is the best alkali atom to choose for gas cell atomic clock operation. This report describes strategies for developing such clocks for space applications and as local oscillators for other high-accuracy atomic clocks.

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DIODE-LASER-PUMPED, GAS-CELL ATOMIC CLOCKS

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Abstract

Recent theoretical calculations suggest that the short-term stability of rubidium, atomic, gas-cell frequency standards could be improved by several orders of magnitude if diode lasers were used for optical pumping. Moreover, the theoretical results predict that rubidium, as opposed to cesium, is the best alkali atom to choose for gas cell atomic clock operation. This paper describes strategies for developing such clocks for space applications and as local oscillators for other high-accuracy atomic clocks.

Introduction

The rubidium gas cell atomic clock has been around for 30 years and is usually thought of as a "mature" technology. Recent theoretical analysis, [1] however, indicates that replacing the rubidium lamp with a laser could yield several orders of magnitude improvement in short-term stability, $0.1\ s < \tau < 100\ s$. How has this tremendous potential gone untapped in lamp-pumped standards? The spectroscopic complexity of the lamp-pumped system makes a detailed analysis of the physics almost impossible. However, the following somewhat simplified description gives clues as to the problem.

The conventional lamp-pumped, buffer-gas cell standard operates in a spectroscopic cacophony composed of two isotopes each with two principal resonance lines (D_1 and D_2) which are further split into two hyperfine components each composed of several unresolved additional hyperfine components. These many lines are each characterized by a width, a position, and a degree of self reversal or optical depth that are all functions of the operational conditions. It is the job of the designer to concoct a witch's brew of buffer gases, different in the lamp, (filter) and cell, to broaden and shift these lines in such a way as to improve upon a coincidental, near overlap of a line in one isotope with a line in the other. It is this overlap that allows the combination of lamp,(filter), and cell to produce the optical pumping necessary for the operation of the standard. Not surprisingly, however, this complex spectrum leads to a situation where the degree of optical pumping achieved is small (some of the undesirable light leads to depumping) and the level of background light is high (contributing noise).

The ultimate stability of a rubidium cell standard can be glimpsed through a very simple argument. Consider only how many rubidium atoms are in a cell, how often each of them can contribute to the signal, and what the resonance linewidth might be. At 50°C, the vapor density of rubidium is about $10^{11}\ cm^{-3}$ and the spin exchange rate is the order of 100/s. This could result in $> 10^{12}$ "clock" transitions per second and a linewidth < 100 Hz. We can then model the atomic shot-noise limited, short-term stability as roughly $\sigma_y(\tau) \approx (Q \cdot S/N)^{-1} \approx 10^{-14}/\sqrt{\tau}$. More elaborate calculations [1] optimizing the microwave power, the optical power and taking into account the effects of laser noise predict similar

performance. Previous experiments, [3] confirmed in the current NIST work, have shown that lasers can indeed produce much higher optical pumping and correspondingly higher microwave/optical double resonance signals while at the same time reduce the amount of light falling on the detector by an order of magnitude or more. These simple experiments provide proof, in principle, of the available potential. The reason they have not produced eye-popping stability is, in part, related to the fact that they have been done with available commercial standards in which the microwave synthesis is not capable of supporting such performance. [4]

Comparing the optimized short-term stability of laser-pumped standards with that actually achieved in lamp-pumped standards may not seem totally fair because conventional lamp-pumped standards have compromised their short-term stability somewhat in order to achieve better long-term stability. However, the laser-pumped standard affords other possibilities (to be discussed) for the control of light shift and, hence, long-term stability. Therefore, it seems justified to discuss their optimized short-term potential.

In Section II we will briefly review the detailed theory, its predictions, and limitations. In section III we will outline a planned experimental project which will build off from existing technology with an eye toward space applications. In Section IV we will outline a project which is directed toward ultimate performance in the 1-200 s region for use as a local oscillator in future "super" clocks.

Theory

The theory as published in Ref. 1 assumes a conventional device in which the lamp is simply replaced by a laser. The laser is assumed to operate continuously while the cell is of the buffer-gas type and is constrained to a minimum cavity volume. A one-dimensional model is developed to account for the laser-induced optical pumping, atomic diffusion to the deactivating walls, collisional relaxation, and the expected noise behavior of the laser.

For a given laser intensity and noise, the model is used to predict clock stability as cell temperature and microwave power are optimized. The locus of such points calculated for ^{87}Rb is plotted in Figure 1 as a function of laser power density. The line labeled "with light shift" assumes the FM noise of a solitary laser diode (linewidth $\simeq$ 50 MHz). The curve labeled "shot noise alone" is presented to suggest the results that may be achievable with a system in which the laser FM noise is reduced; e.g. enhanced cavity Q laser, extended cavity laser or gated light operation.

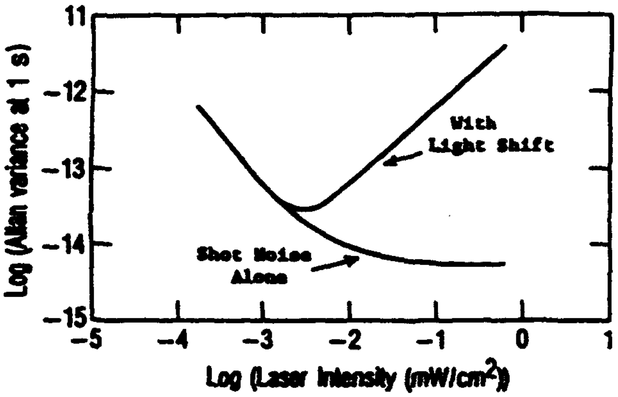

Figure 1. The Allan variance at 1 s for diode-laser pumped rubidium frequency standard with resonance cell temperature and microwave Rabi frequency chosen in such a way that the clock's stability is optimized. The curve labeled "with light shift" assumes the FM noise of a solitary laser diode couples to the clock stability through the light shift term. The curve labeled "shot noise alone" is displayed to represent the clock stability when an advanced, FM controlled laser is used.

With lamp pumping, only rubidium has been developed into a commercial cell standard. This is because the needed filtering, is conveniently available only through the coincidental, near overlap of spectroscopic lines in rubidium. With diode lasers, no such filter is needed, and other atoms can be considered. [2] Figure 2 looks at predicted clock stability achievable with several isotopes of both rubidium and cesium. Rubidium remains the atom of choice for optically pumped cell standards. This results from the fact that its lower nuclear spin more than compensates for the higher transition frequency and hence line Q in cesium.

The model calculations presented here and in Ref. 1 have a number of limitations, but their general predictions should not be altered. In fact, preliminary experiments with lasers verify the potential. Although a full 3-D gas-cell clock signal model now exists, [5] the diode laser calculations employed a 1-D signal model. Consequently, the optical and microwave radial field distributions were not included. This should have only minimal effect on the predicted values. On the other hand, the

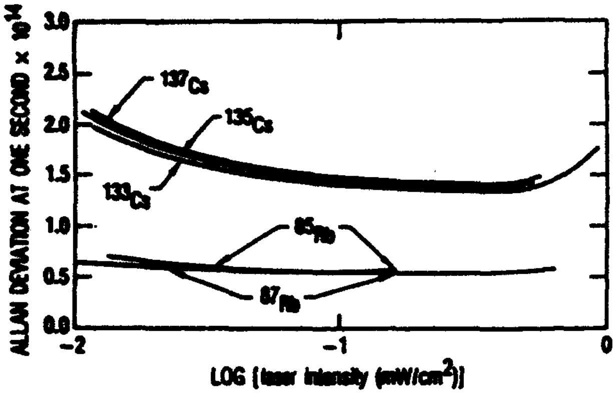

Figure 2. Comparison of predicted, optimized stability (Allan variance at 1 s) for several isotopes of cesium and rubidium as a function of laser power.

calculations were based on a minimum microwave cavity volume, and theoretical predictions [2] suggest that increasing the cavity volume improves short-term performance. Finally, the model assumes cw excitation in a buffer gas cell. Large regions of parameter space remain unexplored. Evacuated, wall-coated cells allow the atoms to average over some of the field inhomogeneities that contribute to long-term instability problems in existing standards. Furthermore, the laser can be more easily gated than a lamp and in an evacuated cell this leads to a fundamental elimination of the light shift effect. Also, the rapidly advancing field of diode laser technology has already produced solitary lasers which have substantially lower noise than those used in these calculations. [6]

Rubidium Clocks for Space Applications

The Aerospace Corporation is studying the space applications of diode-laser-pumped clocks. The project will, therefore, be principally aimed at small, robust devices that can withstand relatively high temperatures. These restrictions limit the regions of parameter space that can be used: *small* puts limits on the cavity and cell size, *robust* requires a certain simplicity of design, and *high temperature* may limit the use of wall coated cells. The program intends to make changes in the rubidium clock physics package incrementally. Phase 1 will simply replace the lamp in a commercial clock and attempt to improve on past results. As pointed out above, previous experiments have shown that it is easy to achieve dramatic improvement in the degree of optical pumping and reduction in the background light, whereas utilizing the much higher signal-to-noise ratio will require new electronics. Following phase 1, a second phase will examine the use of more radically changed devices perhaps employing pulsed pumping and/or evacuated cells with chemisorbed coatings to improve upon the long-term stability of the clock.

Rubidium Clocks as Local Oscillators

Future "super clocks" will probably employ trapped atoms or ions and exhibit extremely narrow atomic resonances with very high signal-to-noise ratios. Such clocks are expected to have atomic limited, short-term performance characterized by $\sigma_y(\tau) < 10^{-14}\tau^{-1/2}$ and use modulation rates from 0.1 to 0.001 Hz. The NIST laser-pumped rubidium cell program is primarily investigating development of a "local oscillator" for such a standard. It is directed toward a laboratory device in which ultimate performance in the $1\ s < \tau < 1000\ s$ range is the goal; size, weight, complexity and power consumption are of secondary importance.

In the first phase, extended cavity diode lasers will be used to control the FM noise of the laser and reduce the light shift noise in the rubidium cell standard. A new microwave synthesis scheme has been developed to provide the ultra-low phase noise microwave signal necessary to support this standard. [7] The enhanced levels of optical pumping already observed at low light levels together with the new synthesizer should produce dramatic stability results. Advancing several orders of magnitude in stability will probably reveal problems not encountered before. Therefore, future directions (pulsed optical pumping, wall coated cells, etc.) will await the outcome of the initial tests.

Summary

Theoretical models indicate that laser optical pumping in rubidium gas cell atomic clocks afford the possibility for several orders of magnitude improvement in short-term performance over conventional lamp-pumped devices. We have begun projects to investigate this potential. Preliminary experiments indicate that the short-term stability is achievable. Additionally, the spatial and temporal coherence of the laser affords possibilities for control of the long-term instability caused by light shift; that is, new geometries and cell types are possible because of the lasers spatial coherence while the temporal coherence and tunability allow one to operate at carefully chosen conditions to minimize light shift. All of this may allow total performance

from a rubidium cell standard that rivals active hydrogen masers.

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